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Chemical and Physical Properties of
Tropical Biomass Affecting Fire
Behavior and Emissions

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**CHEMICAL AND PHYSICAL PROPERTIES OF TROPICAL BIOMASS AFFECTING
FIRE BEHAVIOR AND EMISSIONS**

**FINAL REPORT
INT-92664-RJVA**

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ABSTRACT

Deforestation in the Brazilian Amazon has resulted in the conversion of >230,000 km² of tropical forest, yet little is known on the quantities of biomass consumed or the losses of nutrients from the ecosystem. We quantified the aboveground biomass, nutrient pools and the effects of biomass burning in four slashed primary tropical moist forests in the Brazilian Amazon. Total aboveground biomass (TAGB) ranged from 292 Mg ha⁻¹ to 436 Mg ha⁻¹. Coarse wood debris (>20.5 cm diam.) was the dominant fuel component. However, structure of the four sites were variable. Coarse wood debris comprised from 44% to 69% of the TAGB, while the forest floor (litter and rootmat) comprised from 3.7 to 8.0% of the TAGB. Total biomass consumption ranged from 42 to 57%. Fires resulted in the consumption of >99% of the litter and rootmat yet <50% of the coarse wood debris.

Dramatic losses in carbon, nitrogen, and sulphur were quantified with lower quantities of P, K, and Ca lost by combustion processes. Carbon losses from the ecosystem were 58 to 112 Mg ha⁻¹; nitrogen losses ranged from 817 to 1605 kg ha⁻¹ and sulphur losses ranged from 92 to 122 kg ha⁻¹. This represents losses that are as high as 56%, 68%, and 49% of the total aboveground pools of these nutrients, respectively. Losses of P were as high as 20 kg ha⁻¹ or 32% of the aboveground pool. Losses to the atmosphere arising from primary slash fires were highly variable due to site, climatic fluctuations, and anthropogenic influences. However, on an areal basis, fires in primary slashed forests globally result in among the highest total losses of nutrients from a single fire. In addition, the proportion of the total nutrient pool lost from slash fires is higher

in this ecosystem compared to other ecosystems due to a higher percentage of nutrients stored in aboveground biomass.

KEYWORDS: Tropical forests, biomass burning, carbon cycling, nutrient cycling, slash-and-burn.

INTRODUCTION

Deforestation and biomass burning of tropical forests continues to be among the most devastating of anthropogenic activities with respect to the diminution of biological diversity, site productivity and potential, and influence on global biogeochemical cycles. Utilizing remote sensing, recent estimates of deforestation in the Amazon suggest that from 230,000 (through 1988) to 415,000 km² (through 1990) had been deforested in the Brazilian Legal Amazon (Fearnside 1992a, Skole and Tucker 1993). In addition, improved, yet controversial, estimates of total aboveground biomass (TAGB) for Amazonian forests are available (Brown and Lugo 1992, Fearnside 1992a, Fearnside 1992b). Direct measurements of the biomass of Amazon forests range from 143 to 666 Mg ha⁻¹ (Fearnside et al. 1993). Average TAGB in Amazonian tall evergreen tropical forests have been variously estimated to range from 227 to 394 Mg ha⁻¹ (Brown and Lugo 1993, Fearnside 1992a).

While estimates of the extent of deforestation and TAGB have improved, little quantitative information exists on biomass of slashed forests, quantities of biomass consumed, mass of nutrient pools subjected to fire or the losses of nutrients during fire. Few estimates of biomass loss by combustion processes have been derived from quantitative sources (Crutzen and Andreae 1990, Detwiler and Hall 1988, Houghton 1991). Estimates of biomass consumption by fires in primary slashed forests ranged from 28 to 40%. Even less data are available on nutrient concentration, mass and losses from TAGB pools during combustion processes. These pools are known to be significant nutrient sinks in maintaining the nutrient balance of tropical forests (Jordan and Uhl

1978, Jordan 1982). Because many soils of the Amazon Basin are highly weathered, the nutrient balance and hence site productivity is largely maintained through atmospheric deposition (Jordan 1982, Vitousek and Sanford 1986, Bruijnzeel 1991). Because of the efficient cycling of nutrients within tropical forests, coupled with low rates of nutrient inputs, anthropogenic disturbances which result in a huge pulse of nutrient losses have the potential to severely limit ecosystem recovery, as well as influence succession processes and the future potential as a C sink.

To address these issues, we sampled the influences of fire in four slashed primary forests of the Brazilian Amazon. Our objectives were to quantify: (1) the total aboveground biomass prior to, and after slash fires, (2) quantify the concentration, distribution, and mass of nutrient pools of the aboveground biomass, and (3) quantify distribution and mass of residual pools and, (4) the nutrient losses that occurred during combustion processes.

METHODS

Study Area

The study areas were located in the Brazilian States of Para and Rondonia. These regions of the Brazilian Amazon have been, and are currently undergoing rapid rates of deforestation (Skole and Tucker 1993). Principal causations of deforestation include pasture conversion, shifting cultivation, and timber exploitation.

The intact primary forests of the area are classified as Floresta tropical perenifolia de terra firme (upland tropical evergreen forest) by Eiten (1983) or as Floresta

ombrofila densa-submontana (Para) and Floresta ombrofila aberta submontana (Rondonia) by Radam (Brazil, Projeto RADAMBRASIL, 1976, 1978).

The first area sampled was near the town of Nova Jacunda, Para ($04^{\circ}3'S$, $49^{\circ}0'W$). This site was cut and burned during the dry season of 1990. The second sampled site was 50 km south of Maraba, Para and was cut and burned in 1991. The third and fourth sites were near the mining village of Santa Barbara and town of Jamari, Rondonia ($\sim 9^{\circ}12'S$, $60^{\circ}3'W$). These sites were approximately 5 km apart from each other; both areas were cut and burned in 1992. Hereafter, these sites will be referred as the Jacunda, Maraba, Santa Barbara, and Jamari sites, respectively.

Climatological data of the nearest stations are from Maraba (approximately 75 km south of the Jacunda site and 50 km north of the Maraba site), and Porto Velho (approximately 100 km northwest of the Santa Barbara and Jamari sites). Mean average precipitation of the two stations is 2088 and 2354 mm, respectively. A pronounced dry season exists from June to September with precipitation normally being <100 mm during these months. Mean average temperature is $26.1^{\circ}C$ and $25.2^{\circ}C$, temperature minima is $22.1^{\circ}C$ and $20.9^{\circ}C$, temperature maxima $31.7^{\circ}C$ and $31.1^{\circ}C$ and mean relative humidity is 82% and 85%, respectively (Departamento Nacional de Meteorologia, Brasil 1992).

Our objective was to sample the environment and influences of anthropogenic fires in a manner that would not be biased by our scientific measurements. All decisions of cutting and burning were left to local landowners. Sites had already been felled when our measurements began. All sites sampled were on areas occupied by small farms ($<1,000$ ha). This kind of use is representative of $\sim 70\%$ and 47% of the land area in

use in Rondonia and Para, respectively (Fearnside 1992a). Land use objectives were different for each site. The Jacunda site was to be utilized the first year for crops (rice, manioc and corn) and then converted to cattle pasture. The Maraba and Jamari sites were cleared with the objective of direct cattle pasture establishment. The Santa Barbara site was cleared for use only as shifting cultivation (rice and manioc). The Jacunda and Santa Barbara sites had not previously been disturbed through timber extraction activities. The Jamari and Maraba sites were bisected by an old logging trail. However, the degree of timber extraction (if any) was undetectable and likely minimal.

All sites were deforested in a similar manner. At the onset of the dry season, the understory was cleared utilizing only hand tools. Following this, large trees were felled utilizing chainsaws. Some trees were left standing in all sites because of their value or those because they are illegal to cut (e.g. Brazil nut, Bertholletia excelsa). Occasionally, trees were cut by chainsaw, yet did not fall. These residual standing trees were not included in biomass measurements. Towards the end of the dry season, 60-70 days following deforestation they were burned. All sites were burned utilizing circle-fire ignition patterns where the perimeter was ignited causing the fires to burn most intensely towards the center. Typically, sites were ignited when the temperature was warmest and relative humidity lowest (1200 to 1400 hrs). Usually, landowners select cloudless days following at least a week without significant precipitation.

Aboveground Biomass

Fuels are defined as equivalent to the aboveground biomass of the slashed primary forests. Fuels were partitioned on the basis of their influence on fire behavior,

value as a nutrient pool, plant morphology, and considerations of sampling approach. Fuels categories include downed wood debris (including vines), attached foliage, litter, rootmat, and residual plants (seedlings and resprouts).

The prefire mass of wood debris, the amounts consumed by fire, and the postfire residual wood debris were estimated nondestructively utilizing planar intersect models modified specifically for each site (Brown and Roussopoulos 1974, Van Wagner 1968). At each site, 32 planar intersect transects were systematically established to ensure sample dispersion through the slashed areas. All transects were marked with small aluminum stakes prior to burning. This facilitated exact relocation and remeasurement following fire. Diameters of all wood particles intersecting each sample plane were measured. We partitioned the wood debris into standardized size classes based on their diameter. Wood particle diameter is a good predictor of the rate of moisture loss (e.g., a time-lag constant) and hence relationships to combustion and fire behavior (Deeming et al. 1977). These diameter size classes have also been shown to vary inversely with nutrient concentrations and improve calculations of loss or redistribution by fire (Kauffman et al. 1993, Kauffman et al. 1994). The timelag constant of a fuel particle is defined as the time required for a fuel particle to lose 63% of the difference between its initial equilibrium moisture content under standard conditions of 27°C and 20% relative humidity (Pyne 1984). The diameter classes used to partition wood debris were 1-h (0-0.65 cm), 10-h (0.64-2.54 cm), 100-h (2.55-7.5 cm), 1000-h sound and rotten classes (7.6-20.5 cm) and 10000-h sound and rotten classes (>20.5 cm). Lengths of the sampling plane varied among the wood debris size classes: 1 m for wood particles ≤ 0.64 cm

diameter, 2 m for wood debris 0.65-2.54 cm diameter; 5 m for wood debris 2.55-7.6 cm diameter; and 11 m for all coarse wood particles ≥ 7.6 cm diameter. The diameter of each coarse wood debris particle intercepting the plane was measured to the nearest half centimeter. For the three wood debris size classes <7.6 cm diameter, a quadratic mean diameter was utilized for equations through measurement of 100 particles of each size class at each site. Thereafter, for these classes we counted the number of particles that intersected the sampling plane. Bias due to fuel particle tilt and slope was corrected for as outlined in Van Wagner (1968) and Brown and Roussopoulos (1974). Thirty randomly collected samples of each size class were measured for specific gravity (particle density) at each site.

The biomass of attached foliage (i.e. leaves, flowers, and seeds that remained attached to the slashed woody debris) was ascertained through determination of the ratio between its biomass and that of the 0-0.64 cm diameter wood particles. At each site, 50 randomly collected samples of the 1-h timelag fuels and their associated attached foliage were collected, oven dried and their mass ratios determined. The mass of attached foliage was then estimated by multiplying the biomass of the 1-h time-lag fuels by this ratio.

The biomass of litter, rootmat (if present), seedlings, and sprouts were destructively sampled through collection of all materials in 25 x 25 cm microplots. A microplot was placed at the 2 m mark of each planar intersect transect (i.e. $n = 32$ plots per site). The mass of litter, rootmat and live plants within each microplot was separated, oven dried and weighed. Following fire, another microplot established 2 m

away from the prefire microplot was collected for determination of the postfire mass of these components.

Ash mass at the Jacunda and Maraba site was measured following methods similar to that of Ewel et al. (1981). Ash depth was measured to the nearest millimeter at 100 random points the day following fire. Ten ash samples of known volume and weight were collected in 10 cm diameter glass petri dishes to determine bulk density. Ash mass was then determined by multiplying depth by mean bulk density. At the Santa Barbara and Jamari sites, ash mass was sampled from within sixteen 50 x 50 cm microplots one day after the fire. A portable electric generator and vacuum cleaner was utilized to collect the ash within each microplot. Given the difficulties in accurately measuring ash depth (without disturbance) and in collection of representative bulk densities of ash, we believe the latter method was a more efficient and representative method of ash quantification.

Nutrient Pools

Aboveground nutrient pools were partitioned into the same classes as aboveground biomass. Prior to burning, five samples of each fuel component were collected at each site. Each of these samples consisted of a composite mix of 10-20 collections of materials. Ash samples were collected in the same manner following fire. At each site five soil samples at depths of 0-2.5 cm and 2.5-10 cm were also collected. Following fire, soils at the Jacunda, Maraba, and Santa Barbara site were re-sampled approximately 1 m away from the prefire soil sampling areas. At the Maraba site, an additional prefire collection at the 10-30 cm depth was also made. Samples for the

calculation of soil bulk density were collected in the same areas as nutrient samples. All samples were air-dried for at least one week, placed in plastic bags and transported to the laboratory for nutrient analysis.

All plant and ash samples were analyzed for total N, P, K, C, S and Ca. Soils at the Santa Barbara and Jamari site were also analyzed for these elements. However, only N was analyzed at the Jacunda site and only C and N was analyzed at the Maraba site. Prior to analysis, plant and ash samples were ground to pass through a 40 mesh screen (0.5 mm) in a Wiley mill. Total N was determined from Kjeldahl digestion (Bremner and Mulvaney 1982). Total Ca, K, and S were determined by atomic absorption (Tabatabai and Bremner 1970). Total P was determined calorimetrically following wet digestion utilizing a Kjeldahl procedure (Watanabe and Olsen 1965). Total C was analyzed by the induction furnace method (Perkin-Elmer 2400 elemental analyzer for the Jacunda and Maraba sites and a Carlo-Erba NA Series 1500 for the Santa Barbara and Jamari sites) (Nelson and Sommers 1982). Organic matter was determined through complete combustion of samples at 500°C for 8 hours in a muffle furnace (Davies 1964).

Fuel moisture content, air temperature, relative humidity, and flame length were recorded at each site prior to, and during the flaming phase of combustion. Moisture content (dry-weight basis) was calculated through collection of 5-10 samples of the following components: soil surface, litter, dicots, attached foliage, wood 0.65-2.54 cm diameter and wood >7.6 cm diameter. Samples were weighed in the field with a portable digital balance. They were then oven dried at 60°C for 5 to 7 days to calculate

dry weight. Air temperature and relative humidity was measured with a sling psychrometer and wind speed was measured with a portable anemometer.

Differences in prefire biomass and nutrient pools, postfire biomass and residual nutrient pools, ash and nutrients lost from the site were tested between the four different slashed primary forests through analysis of variance in a completely randomized design. If significant, the least significant difference multiple range test was utilized to determine statistical significance among the sites sampled ($P \leq 0.10$).

RESULTS

Biomass

Total aboveground biomass of the slashed tropical moist forest ranged from 290 Mg ha⁻¹ to 435 Mg ha⁻¹ (Table 1). Biomass of the Maraba site was ~49% greater than that of the Jacunda or Santa Barbara site even though they are classified as the same forest type. Structure of the forest sites were highly variable as well. For example, wood debris >20.5 cm diameter was the dominant fuel component at all sites (133 to 303 Mg ha⁻¹). However, this component comprised of 69% of the TAGB at Maraba compared to 44% at Jamari. A well developed rootmat was present at the Santa Barbara site (12.7 Mg ha⁻¹). In contrast, rootmats were not present in the two sites sampled in Para. The forest floor (litter layer and rootmat combined) comprised 8% of the TAGB at the Santa Barbara site, but $\leq 4\%$ at the other sites. Fine fuels (i.e., the forest floor, attached foliage, sprouts and seedlings and wood debris ≤ 2.54 cm diam.) ranged from 38 to 52 Mg ha⁻¹. This component comprised 9.5% of the TAGB at the Maraba site, and 17.9% of the TAGB at the Santa Barbara site. While significant differences in TAGB did not

exist when comparing the Para forests combined to the Rondonia forests combined, general structural differences were apparent; the Rondonia forests had a greater proportion of TAGB in fine fuels while the Para forests had a higher proportion in wood debris >20.5 cm diameter (Table 1).

All fires were conducted at the end of the dry season (September) when the majority of burning occurs in these regions (Table 2). All fires were first ignited mid-day when temperatures were warmest (32-40°C) and relative humidity was lowest (37-55%). Moisture contents of the measured dead fine fuels (i.e. those likely to be responsible for the sustained propagation of fire) were well below the threshold of combustion (Uhl and Kauffman 1990). Moisture content of attached foliage ranged from 6 to 10% and moisture content of litter ranged from 2 to 10%. In contrast, the moisture content of litter in an adjacent intact primary forest at the Santa Barbara site was 36%. Coarse wood debris moisture content ranged from 28 to 73%. Total aboveground mass of water in these ecosystems at the time of burning was 109 Mg ha⁻¹ for Jacunda, 292 Mg ha⁻¹ for Maraba, 73 Mg ha⁻¹ for Santa Barbara and 104 Mg ha⁻¹ for Jamari. Fire behavior was highly variable at all sites with flame lengths ranging from 1-30 m and a mean flame length of 8 to 15 m (Table 2). At all sites, the fire completely covered the areas.

Fires consumed 42 to 57% of the TAGB of the slashed primary forest sites. Residual (postfire) TAGB ranged from 140 to 207 Mg ha⁻¹ (Table 1). Ash biomass ranged from 7.2 to 10.9 Mg ha⁻¹. The fine fuel fractions (i.e., those likely consumed during the process of flaming combustion) were consumed at levels of 78 to 100%. In contrast, consumption of coarse wood debris (i.e., that component likely to be consumed

after the passage of the flame front by flaming and smoldering combustion processes) was 16% at the Santa Barbara site. Consumption of this component was 44, 46 and 34% at the Jacunda, Maraba, and Jamari sites, respectively. Given that the water content of fuels and the ratio of water to dry mass was lowest at the Santa Barbara site (Table 2), we would have expected levels of consumption to be highest at this site. However, a significant precipitation event occurred the night following the Santa Barbara fire extinguishing all residual combustion. In contrast, at the other sites where there was no rainfall the week following fires, smoldering combustion of the coarse wood debris continued for >7 days.

The rotten coarse wood debris represents a portion of the dead and downed wood and/or snags originating from the standing forest. This component ranged from 8 to 20 Mg ha⁻¹ of the TAGB and was consumed in greater quantities than sound wood of the same diameter class (43 to 100%). The effects the levels of biomass consumption on land clearing was judged to be satisfactory by each of the landowners.

Nutrient Pools

Nutrient concentrations were typically highest in the non-wood components of the ecosystem which were the most susceptible to complete consumption by fire (Table 3). Concentration of N ranged from 19 to 23 mg g⁻¹ and concentration of P ranged from 0.50 to 0.95 mg g⁻¹ in these components. In contrast, concentration of N and P in sound coarse wood fuels was ~4 and 0.15 mg g⁻¹, respectively. In the sound-wood components, nutrient concentrations were inversely related to stem diameter. Rotten wood debris was significantly higher in concentration of N, S, and Ca than sound wood debris. With the

exception of the rootmat, C did not show any difference in concentration among the various fuel components. C ranged from 49.2 to 50.1% of the biomass among the fuel components except in the rootmat, which had a mean concentration of 34.2%.

Nutrient mass (Figs. 1A-1F) was calculated through multiplication of biomass by the nutrient concentration of samples that were collected on that site. While the means of all sites combined are reported in Table 3, differences in nutrient concentrations between sites were apparent. In all fuel components, concentration of S was lower at the Santa Barbara site. Concentration of N was consistently lower at the Jacunda site compared to the others. In general, the N concentration in fuels was higher at the Rondonia sites than the Para sites. For example, N concentration of fine wood debris (<0.64 cm diam) was 8.0 mg g^{-1} at the Jacunda site but $>13 \text{ mg g}^{-1}$ at the Rondonia sites. Calcium concentrations were consistently lower at the Santa Barbara site than others. For example, concentration in coarse wood debris was 0.83 mg g^{-1} at Santa Barbara and $>2.5 \text{ mg g}^{-1}$ at the others.

The variability of the nutrient concentration of ash was much greater among sites than the unburned materials (Table 4). Nitrogen and C concentration of ash was highest in ash of the Santa Barbara than all others. Similarly, those nutrient components with higher temperatures of volatilization (S, P, Ca, and K) were typically low at the Santa Barbara site. This is likely related to the precipitation event the night of the Santa Barbara fire which halted combustion and perhaps leached some of the water soluble cations out of the ash. The effects of rainfall on the completeness of combustion is apparent through examination of the organic matter concentration of ash at the

Rondonia sites. Organic matter comprised 45% of the ash at Santa Barbara but only 25% of the ash concentration at Jamari.

Typically, the concentration of ash was lower than that of fuels for nutrients with low temperatures of volatilization (N and C), and higher than that of fuel components for nutrients with high temperatures of volatilization (Tables 3 and 4). For example, mean concentration of C was 18 to 33% in ash but ~50% in fuels. Mean concentration of N was approximately similar to that of coarse wood debris at the Jacunda, Maraba, and Jamari sites. Mean concentration of K was ~9 mg g⁻¹ in dicots and 1.6 mg g⁻¹ in coarse wood but 24 to 54 mg g⁻¹ in ash.

Among the four slashed primary forests, there were dramatic differences in the total prefire mass of nutrient pools as well as the partitioning of nutrients within pools (Figs. 1A-1F, Table 5). The total prefire pool of C, S, K, and Ca was significantly greater at the Maraba site than the others. Total aboveground pools ranged from 1401 kg ha⁻¹ at Jacunda to 2427 kg ha⁻¹ at Jamari. The C pool ranged from 58 Mg ha⁻¹ at Santa Barbara to 112 Mg ha⁻¹ at Maraba. Aboveground pools of S ranged from 216 to 392 kg ha⁻¹; aboveground pools of P ranged from 56 to 87 kg ha⁻¹; aboveground pools of K ranged from 432 to 949 kg ha⁻¹; and pools of Ca ranged from 368 to 1274 kg ha⁻¹.

The variability of aboveground nutrient mass among forest sites did not necessarily parallel the differences in total aboveground biomass. This is particularly evident among the N and Ca pools. For example, the aboveground N pool at Jamari was greater than that of the Maraba site even though its TAGB was 73 Mg ha⁻¹ less. While TAGB of the Jacunda site and Santa Barbara sites were similar, the N pool of the

latter exceeded the former by 600 kg ha^{-1} . Conversely, the Ca pool in the Jacunda site was ~ 2.5 -fold greater than the Santa Barbara site (910 versus 368 kg ha^{-1} , Table 5, Fig. 1F).

The proportion of the nutrient pool contained within the fine fuel fractions exceeded their proportional biomass of the ecosystem. At the Jacunda and Jamari sites, the litter layer comprised 4% of the total biomass, but it contained 15% of the N pool. At the Santa Barbara site, fine fuels accounted for 18% of the TAGB but 42%, 36% and 41% of the N, S, and P aboveground pools, respectively.

In general, a greater proportion of nutrients were stored in coarse wood debris at the Para sites than the Rondonia sites. For example, coarse wood comprised approximately 36% and fine fuels comprised approximately 29 to 36% of the aboveground S pool in Rondonia. In contrast, coarse wood comprised 45 to 62% and fine fuels comprised 20 to 25% of the S pools in Para. Coarse wood comprised $<38\%$ of the total Ca aboveground pool at the Rondonia sites and 48 to 63% at the Para sites (Fig. 1F). The mean C:N ratio of TAGB.

Site losses of N were quite dramatic; 817 to 1605 kg ha^{-1} were lost during combustion. Losses of C were 58 to 112 Mg ha^{-1} (Table 5). These represent losses of 51 to 62% of the aboveground N pool and 40 to 56% of the aboveground C pool. Atmospheric inputs of S ranged from 91 to 137 kg ha^{-1} or 35 to 49% of the aboveground pool. P losses from the ecosystem were quite variable; 7 to 32% of the aboveground pool were lost during fire (6 to 20 kg ha^{-1}). Smaller losses of Ca and K were recorded; less than 20% of the aboveground pool of these nutrients were lost by fire. In terms of

mass, inputs of water vapor into the atmosphere was second only to C. Atmospheric inputs of water from fuels during combustion processes was estimated to be 54, 95, 28, and 126 Mg ha⁻¹ for the Jacunda, Maraba, Santa Barbara and Jamari sites, respectively.

Following fire, there were only two significant aboveground pools of nutrients - ash and residual wood debris (Figs. 1A-1F, Table 5). However, this varied among nutrients. Ash accounted for <16% of the aboveground postfire N pool but comprised >54% of the aboveground postfire pool of Ca and K. Ash consisting of fine particles and charcoal comprised only 0.8 to 2.2% of the residual postfire C pool. This is important because this fraction may contain recalcitrant forms of C (charcoal or char) which are resistant to decomposition.

Soil Nutrients

Nitrogen and C concentrations of soils 0-2.5 cm in depth were higher in the Rondonia than the Para sites (Table 6). This followed the same general pattern of higher N concentrations in vegetation of the Rondonia sites. N and C concentrations of soils from the 0-2.5 cm layer at the Jamari sites were twice that of the Maraba site. There was also great variability among the two Rondonia sites. Concentration of S and Ca was significantly higher at the Jamari site than the Santa Barbara site. Again, the relationship between plant and soil nutrient concentration was apparent at these sites (Tables 3, 6). Soils from the 0-2.5 cm layer were consistently higher in nutrient concentration than the 2.5 to 10 cm layer. For example, at the Jamari site, the concentration of Ca and K in the 0-2.5 cm soil layer was over 4-fold and 7-fold greater than in the 2.5-10 cm soil layer.

Preburn surface soil mass (0-10 cm) of nitrogen ranged from 1167 kg ha⁻¹ at Jacunda to 2420 kg ha⁻¹ at Maraba. Soil C stocks of soils to a depth of 10 cm ranged from 28 to 30 Mg ha⁻¹ (Table 7). Soil N pools were approximately equivalent to aboveground N pools while soil C mass was substantially lower than the aboveground pool (Table 5 and 7). Soil C accounted for 11 to 17% of the soil and aboveground pools combined. At the Santa Barbara and Jamari sites, prefire soil nutrient pools (0-10 cm) were 204 and 318 kg ha⁻¹ for S; 120 and 108 kg ha⁻¹ for P; 104 and 163 kg ha⁻¹ for K and 77 and 174 kg ha⁻¹ for Ca. The surface soil pool of S was approximately equivalent to that of aboveground pools. Soil P comprised >63% of the combined aboveground and belowground pool. In contrast, soil pools of K and Ca comprised <25% of the total combined pool of soils and aboveground mass.

There were no significant trends or dramatic changes in total soil N and C following fire in any of the sampled areas (Table 7). At the Santa Barbara site increases in concentrations of P, K, and Ca were measured. However, because of the precipitation event between the fire and our postfire sampling, it is difficult to interpret fire effects from the potential movement of cations from ash to soil surface horizons. Nutrient concentrations of cations in ash at Santa Barbara were consistently at the low end of our samples. Whether this is the result of leaching losses, lower levels of biomass combustion (also due to the rain) or a combination of the two is unknown.

Combining the soil and aboveground nutrient pools provide an insight into ecosystem effects of these slash fires. Nitrogen losses by fire were 25 to 33% of this combined soil and aboveground pool. Losses of C were equivalent to 34 to 48% of this

total pool. Losses of S were ~22% and losses of P, K, and Ca were <10% of the combined pools (Table 5 and 7). While ecosystem losses of K and Ca appear to be small, it is important to note that the majority of the postfire aboveground pool of these nutrients was in the ash; a form highly susceptible to erosion or leaching losses (Table 5).

DISCUSSION

Aboveground Biomass

Total aboveground biomass ranged from 290 to 435 Mg ha⁻¹ and appears to be representative of many tropical moist forests currently being felled in Para and Rondonia. For example, direct measurements of the TAGB of Para forests have been reported to range from 108 to 607 Mg ha⁻¹ (Uhl et al. 1988, Fearnside et al. 1993). In Rondonia, other studies have reported TAGB to range from 328 to 403 Mg ha⁻¹ (Martenelli et al. 1988, Fearnside et al. 1993). In contrast, our estimates tend to be somewhat higher than indirect estimates based upon forest inventories. Brown and Lugo (1992) estimated TAGB of Para and Rondonia forests to be 263 and 252 Mg ha⁻¹, respectively. These lower estimates would be expected since their models did not include trees <10 cm dbh (diameter at 1.3 m), palms, dead coarse wood debris, or the forest floor. In our study, the combined biomass of the forest floor, dicots, and rotten coarse wood debris (a portion of the dead wood legacy from the intact forest) ranged from 33 to 45 Mg ha⁻¹ or 9 to 13% of the TAGB. Our rotten coarse wood debris component (13 to 23 Mg ha⁻¹) is likely to be an underestimate of the dead coarse wood debris that originated from the intact primary forest because some dead wood in forests

would not be rotten. Other studies have reported coarse wood debris in intact "Terra Firme" Amazonian forests to range from 8 to 42 Mg ha⁻¹ of which 39 to 69% was considered sound (Kauffman et al. 1988, Uhl and Kauffman 1990, Uhl et al. 1988). The rotten coarse wood debris was the only large wood fraction that was consumed in high quantities. For example, at the Santa Barbara and Maraba sites, >90% of the rotten coarse wood debris was consumed while <46% of the sound coarse wood debris was consumed. Clearly, these fractions are of importance both in terms of C pools and in their contribution to atmospheric inputs following fire.

The TAGB consumed by fire (i.e., the combustion factor or combustion efficiency) of the four slashed primary forest sites ranged from 42 to 57% (Table 1). The C release from TAGB was 41 to 56% (Table 5, Fig. 1A). These values are higher than those utilized in many studies of net changes of C between terrestrial ecosystems and the atmosphere. For example, Fearnside (1992a) and Crutzen and Andreae (1990) utilized a combustion factor of ~28% to calculate C inputs from slashed primary tropical forest fires. Fearnside (1992a) estimated that 28.4% of the preburn C would be released by fire with 69% being released through decay. Houghton (1991) assumed that 39% of biomass from cleared and harvest sites was burned and 61% released through decay. These estimates of biomass combustion and C release are likely low for regions such as Rondonia and Para where substantial areas are being subjected to deforestation and biomass burning. Conversely, atmospheric inputs of C via decomposition processes are likely greatly overestimated by these studies. In addition, our estimates of biomass release from fire does not include the additional losses arising from the common practice

of "enchoivamento" where following the initial fire, residual quantities of those wood materials that can be moved by hand are piled and then reburned.

Decomposition losses would also likely be retarded following fire because those readily decomposable components of the ecosystem (i.e., fine particles with lower C:N ratios) are consumed in high quantities during burning. The mean C:N ratio for the TAGB prior to fire was 85.4 as compared to 110.5 for the postfire residual biomass (Table 5). The C:N ratio of the fuels that were consumed by fire was significantly lower, 70.2.

Compared to other tropical ecosystems, the combustion efficiency of tropical moist forests is low. In Brazilian tropical dry forests, Kauffman et al. (1993) measured combustion factors of 78 to 88%. The combustion efficiency of Brazilian savannas and woodlands (Cerrado) was 72 to 100% (Kauffman et al. 1994). However, the forest and fuel biomass of Brazilian tropical dry forest and savannas are substantially lower than that of tropical moist forests. In Brazil, biomass of tropical dry forests was 74 Mg ha⁻¹. The TAGB of Brazilian cerrados ranged from 7 to 48 Mg ha⁻¹ (Cummings et al. 1993) and fuel loads ranged from 7 to 10 Mg ha⁻¹ (Kauffman et al. 1994).

Nutrient Pools

The nutrient concentrations of TAGB in slashed primary tropical moist forest was low. The percentage of TAGB compared by nutrients was 0.5 to 0.67% for N, 0.07 to 0.09% for S, 0.02% for P, 0.15 to 0.22% for Ca (Table 5). These concentrations are similar for biomass susceptible to combustion in cerrado ecosystems (Kauffman et al. 1994). However, they are lower than those reported for Brazilian tropical dry forests

where N accounted for ~0.73 to 0.78% and P accounted for 0.05% of the TAGB (Kauffman et al. 1993). Gross TAGB nutrient concentrations for these tropical moist forests are also at the low end of the range, or, in the case of K and S, below the global range reported by Bowen (1979), Crutzen and Andreae (1990), and Deevey (1970).

Because of a relatively high TAGB, nutrient pools susceptible to combustion were dramatically higher in tropical moist forests than either a tropical dry forest or cerrado. For example, aboveground N pools are 1401 to 2427 kg ha⁻¹, 539 to 579 kg ha⁻¹, and 23 to 55 kg ha⁻¹ for Brazilian tropical moist forest, tropical dry forest, and cerrado, respectively (Table 5, Kauffman et al. 1993 and Kauffman et al. 1994).

While nutrient pools susceptible to fire in tropical moist forests are high relative to other tropical ecosystems, they may be equivalent or lower than slashed temperate coniferous forests. For example, the TAGB of primary *Pseudotsuga-Tsuga* forests of northwestern North America ranged from 783 to 1765 Mg ha⁻¹ (Agee and Huff 1987, Grier and Logan 1977). However, vast quantities of wood are often removed by timber harvest in temperate coniferous ecosystems. Therefore, slash biomass is often lower or equivalent in the temperate coniferous ecosystems (e.g., 71 to 356 Mg ha⁻¹, Little and Ohmann 1988) compared to these slashed tropical moist forests.

A paucity of information exists concerning the nutrient losses by slash fires. Losses of C, N, S, and Ca reported in this study are the highest that we could find reported in the literature (Table 8, Kauffman et al. 1992). These represent significant losses with respect to atmospheric/terrestrial interactions as well as significant negative influences on long term site productivity. However, these losses cannot be expected to

be the total losses resulting from slash fires in this ecosystem. While losses during combustion of K, Ca, and P were relatively low compared to those nutrients with a low temperature of volatilization, large quantities of the postfire aboveground pool of these nutrients remained in the form of ash (Table 5). This portion of the residual aboveground nutrient pool is highly susceptible to site losses. For example, Kauffman et al. (1993) reported that 57% of the ash in a burned tropical dry forest was lost 17 days after burning via wind erosion. In addition, reburns are common in the days following slash fires (to further prepare sites for planting) and in the years following for pasture maintenance or reformation of pastures or croplands. These fires will continue the nutrient depletion of the site (Table 8, Kauffman and Cummings in press). The nutrient losses from fires in slashed primary forests are not only among the greatest in terms of mass inputs into the atmosphere, but also in terms of total depletions of the ecosystem pool. We base this on comparisons of losses by fire in relation to the TAGB and soil surface pools combined. For example, we found that N losses by slash fires in tropical moist forests accounted for 25-33% of the TAGB/soil pool. Proportional losses of the same pool by slash fires in tropical dry forest was 20 to 24% (Kauffman et al. 1993). There are tremendous differences when comparing ecosystem losses by anthropogenic fires in slashed forest ecosystems compared to fires of natural fuels in the savanna-woodland complex of the cerrado. Nutrient losses in the Cerrado where frequent fires are a dominant ecological processes was 2.2 to 4.7% of the soil-fuel N pool (Kauffman et al. 1994).

CONCLUSION

Current deforestation rates in the Brazilian Amazon range from 13,800 to 15,000 km² y⁻¹ (Fearnside 1992a, Skole and Tucker 1993). Our estimates of TAGB are similar to those studies of direct measurements where all components were included. However, the combustion factor (42 to 57%) and C inputs (40 to 56%) from these slash fires are higher than currently utilized in modeling global C cycles. Conversely, amounts of residual C present in forms resistant to decomposition (e.g. char, charcoal, elemental or graphitic C, etc.) and therefore a long-term C storage pool is likely lower than previously thought because only 0.8 to 2.2% of the prefire C pool was found in ash. We believe our results are representative of most forests undergoing deforestation in the Brazilian Amazon because of similarities in climate, soils, and land tenure. If so, C emissions from biomass burning in Brazilian forests is likely higher and those from decomposition processes are likely lower than current reported estimates. However, we temper this statement by the recognition that Amazonian tropical moist forests comprise an extremely diverse mosaic of biomass, structural characteristics, nutrient compositions, and nutrient pools that are not likely completely represented by our four sampled sites. Clearly, additional measurements of these parameters are necessary to better understand biomass and nutrient dynamics of fires in Brazilian tropical moist forests.

While these nutrient losses by biomass burning are among the highest reported in the literature, these represent only a fraction of losses when considering cumulative influences of current land use practices. The dominant land use practices in Amazonia today result in the continued depletion or export of nutrients from perturbed sites through purposeful and accidental pasture fires or the reclearing of second-growth

forests. Until feasible alternatives to the current forms of land use are developed and implemented, there can be little hope of decreasing or even preventing an increase in deforestation, biomass burning, and the subsequent impoverishment of this ecosystem and its inhabitants.

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LITERATURE CITED

- Agee JK, Huff MH (1987) Fuel succession in a western hemlock/Douglas-fir forest. Canadian J. of Forest Research 17:697-704.
- Bowen HJM (1979) Environmental chemistry of the elements. Academic Press. London, UK.
- Brazil DNPM (1978) Projeto RADAMBRASIL. Folha SC.20-Porto Velho; Geologia, geomorfologia, pedologia, vegetacao e USO potencial da terra. Depto. Nac. da Producao Mineral. Rio de Janeiro, Brazil. 16:648 pp + Anexo 850 pp.
- Brown JK, Roussopoulos PJ (1974) Eliminating biases in the planar intersect method for estimating volumes of small fuels. Forest Sci. 20:350-356.
- Brown S, Lugo AE (1992) Aboveground biomass estimates for tropical moist forests of the Brazilian Amazon. Interciencia 17:8-18.
- Bruijnzeel LA (1991) Nutrient input-output budgets of tropical forest ecosystems: a review. J. Tropical Ecology 7:1-24.
- Crutzen PJ, Andreae MO (1990) Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles. Science 250:1669-1678
- Davies BE (1974) Loss on ignition as an estimate of soil organic matter. Soil Science Society of America Proceedings 38:150-151.
- Departamento Nacional de Metrologia-Brasil (1992) Normas climatologicas (1961-1990). Ministerio da Agricultura e Reforma Agraria. Brasilia, DF Brasil.
- Deeming JE, Burgan RE, Cohen JD (1977) The national fire danger rating system-1978 USDA Forest Serv. Gen. Tech. Rep. INT-39. Ogden, UT.
- Deevey ES Jr (1970) Mineral cycles. IN: The Biosphere. W.H. Freeman, San Francisco, CA, USA.
- Detwiller RP, Hall CAS (1988) Tropical forests and the global carbon cycle. Science 239:42-47.
- Eiten G (1983) Classificacao da Vegetacao do Brasil. CNPq/Coordenacao Editorial. Brasilia, DF Brasil.
- Ewel J, Berish C, Brown B, Price N, Raich J (1981) Slash and burn impacts on a Costa Rican wet forest site. Ecology 62:876-879.

- Feller MC (1989) Estimation of nutrient loss to the atmosphere from slash burns in British Columbia. Proceedings of the 10th Conference on Fire and Forest.
- Fearnside PM (1992a) Carbon emissions and sequestration in forests: Case studies from seven developing countries. Volume 2: Brazil. U.S. Environmental Protection Agency, Climate Change Division, Washington, DC, USA.
- Fearnside PM (1992b) Forest biomass in Brazilian Amazonia: Comments on the estimate by Brown and Lugo. *Interciencia* 17:19-27.
- Fearnside, PM, Leal N, Fernandes FM (1993) Rainforest burning and the global carbon budget: biomass, combustion efficiency and charcoal formation in the Brazilian Amazon. *J. Geophysical Res.* 98:16,733-16,743.
- Grier CC, Logan RS (1977) Old growth Pseudotsuga menziesii communities of a western Oregon watershed: Biomass distribution and production budgets. *Ecological Monographs* 47:373-400.
- Jordan CF (1982) The nutrient balance of an Amazonian rain forest. *Ecology* 63:647-654.
- Jordan CF, Uhl C (1978) Biomass of a "tierra fire" forest of the Amazon Basin. *Oecologia Plantarum* 13:387-400.
- Kauffman JB, Cummings DL (199_) Fire in the Brazilian Amazon: 2 Biomass, nutrient pools and losses in cattle pastures converted from tropical moist forest. (In preparation).
- Kauffman JB, Cummings DL (199_) Fire in the Brazilian Amazon: 3 Biomass, nutrient pools and losses in slashed second and third growth forests. (In preparation).
- Kauffman JB, Till KM, Shea RW (1992) Biogeochemistry of deforestation and biomass burning. IN: Dunnett DA, O'Brien RJ (eds) *The Science of Global Change: The Impact of Human Activities on the Environment*. American Chemical Soc. Symp. Series 483. pp. 426-456. American Chemical Society, Washington, DC, USA.
- Kauffman JB, Sanford RL, Cummings DL, Salcedo IH, Sampaio EVSB (1993) Biomass and nutrient dynamics associated with slash fires in neotropical dry forests. *Ecology* 74:140-151.
- Kauffman JB, Uhl C, Cummings DL (1988) Fire in the Venezuelan Amazon: 1. Fuel biomass and fire chemistry in the evergreen rainforest of Venezuela. *Oikos* 53:167-175.

- Kauffman JB, Cummings DL, Ward DE (1994) Relationships of fire, biomass and nutrient dynamics along a vegetation gradient in the Brazilian Cerrado. *J of Ecology* (in press).
- Little SN, Ohmann JL (1988) Estimating nitrogen lost from forest floor during prescribed fires in Douglas-fir/western hemlock clearcuts. *For. Sci.* 34:152-164.
- Martinelli LA, Victoria RL, Moreira MZ, Arroda G, Brown IF, Ferreira CAC, Coelho LF, Lima RP, Thomas WW (1988) Implantacao de parcelas para monitoramento de dinamica florestal na area de protecao ambiental, UHE Samuel, Rondonia: Relatorio preliminar. Unpublished report, Centro de Energia Nuclear na Agricultura (CENA), Piracicaba, Sao Paulo, Brazil.
- Nelson, DW, Sommers LE (1982) Total carbon, organic carbon and organic matter. IN: page AL, Miller RH, Keeney DR (eds) Methods of Soil Analysis, Part 2 Chemical and Microbiological Properties. 2nd Ed. Soil Sci. Soc. Amer. Madison, WI., USA.
- Pyne S (1984) Introduction to wildland fire-fire management in the United States. John Wiley and Sons. New York, New York USA.
- Skole D, Tucker C (1993) Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988. *Science* 260:1905-1910.
- Tabatabai MA, Bremner JM (1970) A simple turbidimetric method of determining total sulfur in plant materials. *Agron. J.* 62:805-806.
- Uhl C, Kauffman JB (1990) Deforestation, fire susceptibility, and potential tree responses to fire in the eastern Amazon. *Ecology* 71:437-449.
- Uhl C, Kauffman JB, Cummings DL (1988) Fire in the Venezuelan Amazon. 2: Environmental conditions necessary for forest fires in the evergreen rainforest of Venezuela. *Oikos* 53:176-184.
- Van Wagner CE (1968) The line intersect method in forest fuel sampling. *Forest Science* 14:20-26.
- Van Wagner CE (1973) Height of crown scorch in forest fires. *Canadian J. of Forest Research* 3:373-378.
- Vitousek PM, Sanford RL (1986) Nutrient cycling in moist tropical forest. *Annual Review of Ecology and Systematics* 17:137-167.

Watanabe FS, Olsen SR (1965) Test of an ascorbic acid method for determination of phosphorus in water and NaHCO_3 extracts from soil. Proceedings Soil Science Soc. of Amer. 29:677-678.

Table 1. Total aboveground fuel biomass (Mg ha⁻¹) prior to and following biomass burning in slashed primary tropical moist forests of Para and Rondonia, Brazil. Numbers are mean \pm 1 standard error.

	Jacunda, Para 1990		Maraba, Para 1991		Santa Barbara, Rondonia 1992		Jamari, Rondonia 1992	
	Prefire	Postfire	Prefire	Postfire	Prefire	Postfire	Prefire	Postfire
Litter	11.8 \pm 1.6 ^A	0.0 \pm 0.0 ^A	16.2 \pm 1.4 ^B	0.1 \pm 0.1 ^A	11.0 \pm 1.5 ^A	0.2 \pm 0.1 ^A	11.8 \pm 1.2 ^A	0.1 \pm 0.1 ^A
Rootmat	--	--	--	--	12.7 \pm 1.3 ^A	3.3 \pm 1.2 ^A	3.0 \pm 0.7 ^B	0.0 \pm 0.0 ^B
Total forest floor	11.8 \pm 1.6 ^A	0.0 \pm 0.0 ^A	16.2 \pm 1.4 ^B	0.1 \pm 0.1 ^A	23.4 \pm 2.1 ^C	3.4 \pm 1.2 ^B	14.8 \pm 1.3 ^{AB}	0.1 \pm 0.1 ^A
Dicots	1.1 \pm 0.4 ^A	0.0 \pm 0.0 ^A	0.4 \pm 0.2 ^{AB}	0.0 \pm 0.0 ^A	0.8 \pm 0.4 ^A	0.1 \pm 0.1 ^A	0.8 \pm 0.5 ^A	0.0 \pm 0.0 ^A
Attached foliage	2.8 \pm 0.3 ^A	0.3 \pm 0.2 ^A	4.9 \pm 0.8 ^B	0.0 \pm 0.0 ^A	6.4 \pm 0.8 ^B	0.1 \pm 0.1 ^A	9.0 \pm 1.0 ^C	0.1 \pm 0.1 ^A
Wood Debris (diam cm)								
<0.64	3.5 \pm 0.4 ^A	0.3 \pm 0.2 ^A	3.0 \pm 0.5 ^A	0.1 \pm 0.0 ^A	5.4 \pm 0.7 ^B	0.1 \pm 0.1 ^A	7.6 \pm 0.8 ^C	0.1 \pm 0.0 ^A
0.65-2.54	18.8 \pm 2.0 ^A	3.6 \pm 0.5 ^B	17.2 \pm 3.1 ^A	1.9 \pm 0.5 ^A	15.7 \pm 2.0 ^A	1.2 \pm 2.0 ^A	20.1 \pm 0.4 ^A	1.0 \pm 0.3 ^A
2.55-7.6	31.6 \pm 3.1 ^A	12.9 \pm 1.8 ^A	33.0 \pm 5.2 ^A	11.3 \pm 1.3 ^A	35.9 \pm 3.9 ^A	11.2 \pm 1.7 ^{ab}	54.6 \pm 6.9 ^B	7.5 \pm 1.4 ^B
7.6-20.5 sound	nd	nd	53.0 \pm 6.2 ^A	39.6 \pm 7.3 ^A	65.5 \pm 7.4 ^A	45.5 \pm 5.1 ^A	93.4 \pm 9.6 ^B	45.3 \pm 5.8 ^A
rotten	nd	nd	3.6 \pm 1.3 ^A	0.0 \pm 0.0 ^A	4.5 \pm 1.4 ^A	0.9 \pm 0.6 ^A	3.8 \pm 1.0 ^A	0.9 \pm 0.6 ^A
Total	67.8 \pm 6.4 ^A	49.4 \pm 4.3 ^A	56.6 \pm 6.2 ^A	39.6 \pm 7.3 ^A	70.0 \pm 7.4 ^A	46.0 \pm 5.1 ^A	97.2 \pm 9.6 ^B	46.2 \pm 5.6 ^A
>20.5 sound	nd	nd	283.7 \pm 63.7 ^A	154.1 \pm 52.0 ^A	124.5 \pm 18.3 ^B	102.9 \pm 18.0 ^A	144.7 \pm 27.8 ^B	91.5 \pm 22.0 ^A
rotten	nd	nd	19.5 \pm 10.1 ^A	0.0 \pm 0.0 ^A	8.1 \pm 4.8 ^A	0.0 \pm 0.0 ^A	13.2 \pm 4.4 ^A	9.1 \pm 4.1 ^B
Total	155.0 \pm 34.5 ^A	73.5 \pm 17.1 ^A	303.3 \pm 64.5 ^B	154.1 \pm 520.0 ^A	132.7 \pm 17.8 ^A	102.9 \pm 18.0 ^A	157.8 \pm 27.5 ^B	100.6 \pm 22.4 ^A
Total wood	176.8 \pm 36.2 ^A	139.6 \pm 24.3 ^A	413.1 \pm 71.0 ^B	207.0 \pm 53.7 ^A	259.9 \pm 20.2 ^A	161.3 \pm 18.5 ^A	337.4 \pm 36.3 ^{AB}	155.4 \pm 24.1 ^A
Total biomass	292.4 \pm 35.8 ^A	139.9 \pm 24.3	434.6 \pm 72.2 ^B	207.1 \pm 53.7 ^A	290.2 \pm 20.4 ^A	165.1 \pm 19.2 ^A	361.2 \pm 36.8 ^{AB}	155.4 \pm 24.1 ^A
Ash		8.8 \pm 6.6 ^A		10.9 \pm 1.0 ^B		9.4 \pm 1.4 ^{ab}		7.2 \pm 1.3 ^A

--components not present in the ecosystem.

nd = components not separated during sampling.

Different superscripted capital letters denote a significant difference in biomass among the four forest sites prior to fire. Different superscripted lower case letters indicate a significant difference in biomass among the four sites after fire. Numbers without superscripted letters were not statistically compared.

Table 2. General weather conditions, moisture content of selected fuel particles at the time of burning and the flame length of the flame front during fires in slashed tropical moist forests of Para and Rondonia, Brazil.

	Jacunda, Para	Maraba, Para	Santa Barbara, Rondonia	Jamari, Rondonia
Date of burn	September 9, 1990	September 4, 1991	September 5, 1992	September 23, 1992
Temperature (°C)	40	32	32	32
Relative humidity	41	37	46-55	53
Wind speed (km/hr)	0-10	5-8	0-8	0-13
Moisture content (%)				
Soil surface	7 ± 1	16 ± 2	28 ± 2	35 ± 4
Litter	9 ± 1	2 ± 1	7 ± 1*	10 ± 0.2
Dicots	nd	185 ± 30	144 ± 36	194 ± 40
Attached foliage	8 ± 0.5	6 ± 1	nd	10 ± 2
Wood 0.65-2.54 cm diam	20 ± 3	nd	14 ± 6	13 ± 1
Wood >7.6 cm diam	40 ± 8	48 ± 5	28 ± 3	38 ± 14
Water mass (Mg ha ⁻¹)	109	194	73	125
Water:dry mass ratio	0.37	0.45	0.25	0.35
Flame length (M)	nd	15 ± 3	9 ± 2	8 ± 2

* Moisture content of litter in an adjacent intact forest was 36 ± 2% at this time.

nd = no data collected.

Table 3. Mean nutrient concentrations of aboveground fuel biomass of slashed primary forests. Numbers are means of all samples combined from all sites in Para and Rondonia, Brazil.

Component	Carbon(%)	Nitrogen (mg g ⁻¹)	Sulphur (mg g ⁻¹)	Phosphorus (mg g ⁻¹)	Potassium (mg g ⁻¹)	Calcium (mg g ⁻¹)
Dicots	49.19 ± 0.36	18.69 ± 1.54	1.88 ± 0.11	0.95 ± 0.27	9.39 ± 1.60	3.50 ± 0.81
Litter	49.90 ± 0.87	18.91 ± 1.09	2.26 ± 0.27	0.65 ± 0.04	3.59 ± 0.43	5.94 ± 0.71
Rootmat	34.21 ± 1.88	18.97 ± 1.26	1.74 ± 0.06	0.50 ± 0.07	1.28 ± 0.09	1.08 ± 0.16
Attached foliage	51.10 ± 0.32	23.32 ± 1.89	2.61 ± 0.18	0.92 ± 0.07	6.41 ± 0.61	4.21 ± 0.71
Wood debris (cm diam)						
0-0.64	49.96 ± 0.27	10.54 ± 1.54	1.60 ± 0.01	0.46 ± 0.05	3.89 ± 0.65	4.54 ± 0.67
0.65-2.54	50.17 ± 0.45	7.73 ± 0.51	0.90 ± 0.13	0.27 ± 0.03	2.54 ± 0.30	3.96 ± 0.41
2.55-7.6	49.65 ± 0.34	5.23 ± 0.47	0.71 ± 0.07	0.16 ± 0.03	1.63 ± 0.23	2.26 ± 0.63
>7.6 sound	50.14 ± 0.24	4.17 ± 0.28	0.69 ± 0.07	0.15 ± 0.01	1.60 ± 0.30	2.06 ± 0.63
>7.6 rotten	49.95 ± 0.57	7.85 ± 0.67	0.96 ± 0.16	0.15 ± 0.01	1.36 ± 0.05	3.78 ± 0.81

Table 4. Nutrient and organic matter concentration of ash following fires in slashed primary tropical moist forests of Para and Rondonia, Brazil. Numbers are mean \pm 1 standard error.

<u>Component</u>	<u>Jacunda, Para</u>	<u>Maraba, Para</u>	<u>Santa Barbara, Rondonia</u>	<u>Jamari, Rondonia</u>
Nitrogen (mg g ⁻¹)	5.44 \pm 0.82	5.44 \pm 0.73	16.69 \pm 0.29	5.55 \pm 1.17
Carbon (%)	18.75 \pm 1.04	20.91 \pm 6.01	33.20 \pm 4.33	20.27 \pm 3.65
Sulphur (mg g ⁻¹)	42.4 \pm 0.46	9.86 \pm 1.24	2.76 \pm 0.20	5.04 \pm 0.39
Phosphorus (mg g ⁻¹)	20.3 \pm 0.33	4.97 \pm 0.52	2.56 \pm 0.15	5.34 \pm 0.45
Potassium (mg g ⁻¹)	23.89 \pm 3.85	53.40 \pm 12.12	28.52 \pm 10.44	54.07 \pm 8.27
Calcium (mg g ⁻¹)	54.07 \pm 9.33	67.50 \pm 10.47	22.06 \pm 3.36	76.54 \pm 8.51
Organic matter (%)	nd	nd	45.34 \pm 5.56	24.87 \pm 4.06

nd = no data.

Table 1. Dynamics of selected aboveground nutrient pools before and after burning slashed primary tropical moist forest, Para and Rondonia, Brazil.

	<u>Jacunda, Para</u>	<u>Maraba, Para</u>	<u>Santa Barbara, Rondonia</u>	<u>Jamari, Rondonia</u>
NITROGEN (Kg/ha)				
Total pool-prefire	1401.4 ± 130.4 ^a	2327.3 ± 329.1 ^b	2063.8 ± 118.7 ^{ab}	2426.9 ± 195.8 ^b
% of TAGB	0.50	0.53	0.71	0.67
Residual fuels-postfire	537.2 ± 91.9 ^a	888.5 ± 223.8 ^a	842.6 ± 103.5 ^a	782.3 ± 116.9 ^a
Released from biomass	864.2 ± 79.6 ^a	1438.7 ± 244.9 ^{ab}	1221.1 ± 119.6 ^a	1644.5 ± 150.8 ^b
Ash	46.83 ± 3.4 ^a	51.5 ± 5.5 ^a	157.0 ± 23.6 ^b	40.06 ± 7.19 ^a
Residual + ash	584.8 ± 91.9 ^a	940.1 ± 224.7 ^a	999.63 ± 101.42 ^a	822.37 ± 116.4 ^a
Site loss	816.6 ± 79.6 ^a	1387.2 ± 245.5 ^{ab}	1064.2 ± 116.5 ^a	1604.5 ± 150.3 ^b
CARBON (Mg/ha)				
Total pool-prefire	147.6 ± 18.1 ^{ab}	218.2 ± 36.3 ^a	142.1 ± 10.1 ^b	178.9 ± 18.2 ^{ab}
% of TABB	50.5	49.7	48.9	49.6
Residual fuels-postfire	69.9 ± 12.4 ^a	104.0 ± 27.0 ^a	81.32 ± 9.4 ^a	77.2 ± 12.0 ^a
Released from biomass	77.7 ± 12.4 ^{ab}	114.2 ± 26.04 ^a	60.8 ± 8.5 ^b	101.8 ± 12.6 ^a
Ash	1.6 ± 0.2 ^{ab}	2.28 ± 0.22 ^b	3.1 ± 0.3 ^c	1.5 ± 0.2 ^a
Residual + ash	71.5 ± 39.2 ^a	106.3 ± 27.0 ^a	84.4 ± 9.4 ^a	78.6 ± 12.0 ^a
Site loss	76.0 ± 9.7 ^{ab}	111.9 ± 26.1 ^a	57.6 ± 8.3 ^b	100.3 ± 12.6 ^{ab}
SULPHUR (Kg/ha)				
Total pool-prefire	250.7 ± 25.8 ^a	392.1 ± 59.9 ^b	215.6 ± 13.1 ^a	251.8 ± 22.1 ^a
% of TAGB	0.085	0.091	0.070	0.070
Residual fuels-postfire	104.3 ± 18.1 ^{ab}	162.2 ± 42.0 ^a	98.1 ± 11.9 ^a	90.4 ± 13.8 ^a
Released from biomass	146.5 ± 14.8 ^{ab}	229.9 ± 43.9 ^a	117.5 ± 12.2 ^b	161.3 ± 6.0 ^b
Ash	37.4 ± 2.6 ^a	93.4 ± 9.9 ^b	25.9 ± 2.7 ^a	39.0 ± 4.9 ^a
Residual + ash	141.6 ± 18.1 ^a	155.6 ± 44.8 ^b	124.0 ± 14.1 ^a	129.5 ± 14.1 ^a
Site loss	109.1 ± 14.8	136.5 ± 45.8	91.6 ± 11.7	122.3 ± 16.4

Table (Continued)

	<u>Jacunda, Para</u>	<u>Maraba, Para</u>	<u>Santa Barbara, Rondonia</u>	<u>Jamari, Rondonia</u>
PHOSPHORUS				
Total pool-prefire	62.2 ± 6.0 ^{ab}	87.1 ± 12.4 ^b	56.0 ± 3.3 ^a	62.8 ± 5.2 ^{ab}
% of TAGB	0.02	0.02	0.02	0.02
Residual fuels-postfire	24.5 ± 4.2 ^a	34.1 ± 8.6 ^a	22.8 ± 2.8 ^a	20.4 ± 3.2 ^a
Released from biomass	37.7 ± 3.6 ^{ab}	53.0 ± 9.1 ^a	33.1 ± 3.1 ^b	42.3 ± 3.9 ^{ab}
Ash	17.9 ± 1.3 ^a	47.1 ± 5.0 ^c	22.2 ± 2.2 ^a	34.7 ± 4.0 ^b
Residual + ash	42.4 ± 4.2 ^a	81.2 ± 10.7 ^b	45.1 ± 3.5 ^a	55.2 ± 5.8 ^a
Site loss	19.8 ± 3.6 ^a	5.9 ± 10.7 ^a	10.9 ± 3.5 ^a	7.6 ± 6.0 ^a
POTASSIUM				
Total pool-prefire	555.8 ± 59.0 ^a	948.9 ± 155.5 ^b	431.9 ± 26.9 ^b	523.6 ± 44.7 ^a
% of TAGB	0.19	0.22	0.15	0.15
Residual fuels-postfire	234.2 ± 40.9 ^{ab}	434.5 ± 112.8 ^a	181.2 ± 21.4 ^b	172.2 ± 26.1 ^b
Released from biomass	321.5 ± 33.9 ^{ab}	514.3 ± 111.5 ^c	250.7 ± 25.4 ^a	351.3 ± 34.0 ^{abc}
Ash	210.5 ± 14.7 ^a	506.0 ± 53.7 ^b	247.6 ± 24.0 ^a	315.8 ± 32.0 ^a
Residual + ash	444.8 ± 40.8 ^a	940.5 ± 132.8 ^b	428.8 ± 32.3 ^a	488.0 ± 39.8 ^a
Site loss	111.0 ± 33.9 ^a	8.3 ± 127.3 ^a	3.09 ± 29.7 ^a	35.5 ± 48.2 ^a
CALCIUM				
Total pool-prefire	909.8 ± 101.4 ^a	1274.2 ± 195.1 ^b	367.5 ± 23.3 ^c	926.8 ± 81.8 ^a
% of TAGB	0.31	0.29	0.129	0.26
Residual fuels-postfire	403.0 ± 69.7 ^a	526.5 ± 133.6 ^a	145.7 ± 17.0 ^b	342.5 ± 51.5 ^a
Released from biomass	506.8 ± 57.1 ^{ab}	747.8 ± 145.8 ^a	221.9 ± 24.4 ^b	584.3 ± 60.6 ^b
Ash	476.5 ± 33.3 ^a	639.6 ± 67.9 ^b	191.5 ± 18.6 ^a	485.5 ± 56.0 ^a
Residual + ash	879.49 ± 69.7 ^{ab}	1166.1 ± 159.7 ^b	337.2 ± 24.4 ^c	828.0 ± 89.3 ^a
Site loss	30.3 ± 57.1 ^a	108.14 ± 166.3 ^a	30.3 ± 25.6 ^a	98.8 ± 87.5 ^a

Table 6. Surface soil nutrient concentration (mg g^{-1}) in slashed primary forests of Para and Rondonia, Brazil. Numbers are mean and standard error.

	<u>Jacunda, Para</u>		<u>Maraba, Para</u>		<u>Santa Barbara, Rondonia</u>		<u>Jamari, Para</u>
	Prefire	Postfire	Prefire	Postfire	Prefire	Postfire	Prefire
<u>Soil Depth (cm)</u>			NITROGEN (mg g^{-1})				
0-2.5	1.37 \pm 0.12	1.08 \pm 0.08	2.34 \pm 0.24	2.48 \pm 0.26	3.96 \pm 0.33	4.10 \pm 0.37	4.79 \pm 0.39
2.5-10	0.93 \pm 0.08	0.86 \pm 0.64	1.87 \pm 0.15	1.87 \pm 0.16	2.52 \pm 1.57	1.92 \pm 0.12	2.52 \pm 0.17
10-30			1.05 \pm 0.03	nd			
			CARBON (mg g^{-1})				
0-2.5			30.11 \pm 5.47	27.37 \pm 2.58	54.86 \pm 5.93	52.51 \pm 6.24	62.65 \pm 73.46
2.5-10			24.34 \pm 2.26	20.78 \pm 1.41	31.93 \pm 22.87	23.01 \pm 1.87	29.08 \pm 2.24
10-30			12.18 \pm 0.30				
			SULPHUR (mg g^{-1})				
0-2.5					0.35 \pm 0.02	0.36 \pm 0.02	0.49 \pm 0.04
2.5-10					0.23 \pm 0.04	0.20 \pm 0.01	0.37 \pm 0.02
			PHOSPHORUS (mg g^{-1})				
0-2.5					0.16 \pm 0.01	0.27 \pm 0.06	0.22 \pm 0.02
2.5-10					0.15 \pm 0.00	0.17 \pm 0.01	0.11 \pm 0.01
			POTASSIUM (mg g^{-1})				
0-2.5					0.17 \pm 0.01	0.30 \pm 0.05	0.50 \pm 0.05
2.5-10					0.12 \pm 0.02	0.08 \pm 0.00	0.11 \pm 0.01
			CALCIUM (mg g^{-1})				
0-2.5					0.21 \pm 0.02	0.25 \pm 0.05	0.65 \pm 0.08
2.5-10					0.06 \pm 0.02	0.13 \pm 0.00	0.08 \pm 0.01











Table 7. Soil nutrient mass (kg ha^{-1}) in slashed primary forests of Para and Rondonia, Brazil. Numbers are mean and standard error.

	<u>Jacunda, Para</u>		<u>Maraba, Para</u>		<u>Santa Barbara, Rondonia</u>		<u>Jamari, Para</u>
	Prefire	Postfire	Prefire	Postfire	Prefire	Postfire	Prefire
<u>Soil Depth (cm)</u>			NITROGEN (kg ha^{-1})				
0-2.5	368 \pm 13	290 \pm 11	628 \pm 23	665 \pm 24	776 \pm 26	803 \pm 27	938 \pm 31
2.5-10	799 \pm 22	733 \pm 21	1603 \pm 45	1603 \pm 45	1479 \pm 49	1129 \pm 37	1482 \pm 49
10-30	2049 \pm 106	1921 \pm 100	2683 \pm 139				
			CARBON (kg ha^{-1})				
0-2.5			6.95 \pm 0.98	6.21 \pm 0.57	10.8 \pm 0.4	10.3 \pm 0.3	12.3 \pm 0.4
2.5-10			20.63 \pm 1.91	14.16 \pm 0.96	18.8 \pm 0.6	13.5 \pm 0.5	17.1 \pm 0.1
10-30			28.75 \pm 0.71	nd			
			SULPHUR (kg ha^{-1})				
0-2.5					69.5 \pm 2.3	72.0 \pm 2.3	97.0 \pm 3.2
2.5-10					134.8 \pm 4.4	123.1 \pm 4.1	221.4 \pm 7.3
			PHOSPHORUS (kg ha^{-1})				
0-2.5					31.4 \pm 1.0	52.9 \pm 1.8	43.1 \pm 1.4
2.5-10					88.2 \pm 2.9	100.0 \pm 3.3	64.7 \pm 2.1
			POTASSIUM (kg ha^{-1})				
0-2.5					33.3 \pm 1.1	58.8 \pm 2.0	98.0 \pm 3.2
2.5-10					70.6 \pm 2.3	47.0 \pm 1.6	64.7 \pm 2.1
			CALCIUM (kg ha^{-1})				
0-2.5					41.6 \pm 1.4	49.0 \pm 1.7	127.4 \pm 4.2
2.5-10					35.3 \pm 1.2	76.4 \pm 2.5	47.0 \pm 1.6

Table 8. Nutrient losses through biomass burning of selected tropical and temperate ecosystems. Losses are reported in Mg ha⁻¹ for C and kg ha⁻¹ for all other nutrients.

<u>Site</u>	<u>C</u>	<u>N</u>	<u>P</u>	<u>S</u>	<u>K</u>	<u>Ca</u>	<u>Source</u>
Cerrado (savanna-woodland and gradient), Brazil	2.6-3.3	5-22	0.2-0.7	2.6-3.0	5.8-7.9	4.7-10.8	Kauffman et al. 1994
Tropical dry forest-slash, Brazil	25-32	428-530	1-21	nd	nd	nd	Kauffman et al. 1993
Temperate coniferous forest slash, Canada	nd	10-982	2-77	nd	0-76	4-211	Feller 1989
Cattle pastures, Brazil	11-21	122-261	1-16	9-25	11-32	0-13	Kauffman and Cummings (in press)
Tropical second-growth slash, Costa Rica	16	490	0	0	0	0	Ewel et al. 1981
Tropical second-growth forests, Brazil	23-47	178-587	2-20	27-44	20-95	10-124	Kauffman and Cummings (in press)
Tropical primary forest, Para	76, 112	816, 1387	6, 20	109, 137	8, 11	30, 108	This study
Tropical primary forest, Rondonia	58, 100	1064, 1605	8, 11	92, 122	3, 36	30, 99	This study

nd = data not collected.

Figure 1A-1F. Nutrient pools of primary tropical moist forest slash before and after fires in Para and Rondonia, Brazil. The vertical lines represent one standard error of the total nutrient pools. Litter is signified by , rootmat by , dicots by , attached foliage by , wood debris 0-0.64 by , 0.65-2.54 by , 2.55-7.6 by , 7.6-20.5 by , >20.5 by , and ash by .

